BULLETIN OF THE POLISH ACADEMY OF SCIENCES
TECHNICAL SCIENCES, Vol. 58, No. 4, 2010
DOI: 10.2478/v10175-010-0051-1

Reflectometric measurements of thermally expanded core area

M. RATUSZEK*, Z. ZAKRZEWSKI, and J. MAJEWSKI

Department of Telecommunications, University of Technology and Life Sciences, 7 Kaliskiego St., 85-796 Bydgoszcz, Poland

Abstract. In this work an analysis method of one-way optical time domain reflectometer (OTDR) measurements has been presented. This method uniquely confirms mode field radii matching in diffusion transit area of the thermally expanded core (TEC) of thermally connected single mode telecommunication fibers. A comparison of reflectometric measurements with theoretical calculations of losses in TEC areas has been demonstrated.

Key words: loss measurement, optical fiber splicing, reflectometry, splicing loss.

1. Introduction

During connecting telecommunication fibers, with the assumption of the lack of transit area of TEC area there can occur between fibers: mismatch of mode field radii, axes shifts, gaps or slopes which are the sources of splice losses [1].

A thermal connection (for example, splicing in electric arc) excludes gaps or slopes. In thermally connected, weakly guiding fibers (with the assumption of the lack of transit area), losses result only from mismatch of mode field radii or/and axes shift – Fig. 1. The most frequent cause of losses in the splice is mismatch of mode field radii of the connected fibers and then, with the assumptions that fibers are connected centrically and the distribution of the basic mode field LP_{01} can be approximated by Gaussian distribution, the value of losses resulting from mode fields mismatch can be obtained as [2]:

$$A_\alpha\,(\mathrm{dB}) = -10\log\left[\left(2W_1W_2/\left(W_1^2+W_2^2\right)\right)^2\right], \quad (1)$$

where W_1, W_2 – mode field radii of connected fibers in the point of contact.

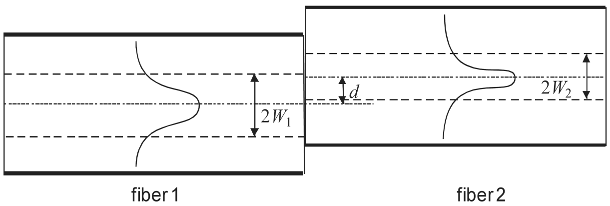

Fig. 1. Connection with axial shift d, of two different cylindrical fibers with weakly guiding and circular cross-section

During connecting fibers whose axes are shifted by quantity d – Fig. 1, the splice loss is [2]:

$$A_\alpha\,(\mathrm{dB}) = 20\log\left(\frac{W_1^2+W_2^2}{2W_1W_2}\right)+4.34\left(\frac{2d^2}{W_1^2+W_2^2}\right), \quad (2)$$

with $W_1 = W_2$ and $d = 0$, the splice loss is equal to zero.

In order to avoid losses connected with differences resulting from mode field dimensions it is necessary to match them. To do it, a transit area must be created in the connected fibers. In this area there will take place equalization (matching) of mode fields. For this purpose, it is possible e.g. to use work consuming methods of welding in, between the spliced fibers, pieces of fibers with successively increasing or decreasing mode field radii [3].

However, it is better to create, by means of controlled diffusion of the core dopant, thermally diffused expanded core area TEC in which mode fields matching occurs [4–6] – Fig. 2.

The method of measurement of losses due to fiber connection which is most frequently used in telecommunication fiber networks is a reflectometric measurement.

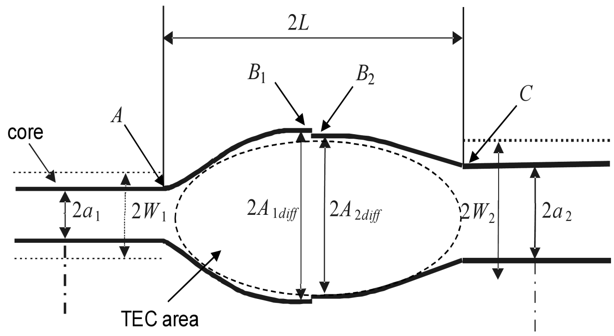

Fig. 2. Schematic illustration of thermally diffused expanded core area

2. Reflectometric measurement of splices without thermally expanded core area

The principle of operation of optical time domain reflectometer, involves emission of many short optical impulses into the fiber splice (multi or single mode) and recording intensity of the light returning from the fiber in the form of "optical echo" that is, power backscattered (Rayleigh backscattered [7]) and reflected in the fiber power.

Backscattered power detected by a reflectometer from a point of route directly before the splice is [7]:

$$P_1 = P_0S_1\exp\left(-2\alpha_1L_1\right), \quad (3)$$

*e-mail: ratuszek@utp.edu.pl

where P_0 – the initial power level (dBm), L – the fiber length (km), α – the attenuation coefficient (1/km), S – the backscatter coefficient, the latter being given by [8]:

$$S = \left(\frac{3}{2}(NA)^2\right) \Big/ \left(\left(\frac{W}{a}\right)^2 V^2 n^2\right), \tag{4}$$

where NA – is the numerical aperture, W – the mode field radius, a – the core radius, V – normalized frequency, n – the core refractive index.

The normalized frequency of the fiber is defined as usual [1]:

$$V = kan\sqrt{2\Delta} = kaNA, \tag{5}$$

where $k = 2\pi/\lambda$, λ – the wavelength, $\Delta = \left(n^2 - n_c^2\right)/2n^2$, n_c – the refractive index of the cladding.

Substituting (5) to (4) one obtains (index 1 denotes input fiber – before the splice):

$$S_1 = 0.038\,(\lambda/n_1 W_1)^2\,, \tag{6}$$

where λ – length of wave on which measurement is being taken, n_1 – refractive index in the core of input fiber, W_1 – mode field radius of the input fiber.

The backscattered power detected by OTDR from a point immediately following the splice is given by [9]:

$$P_2 = P_0 S_2 \eta_{12}\eta_{21} \exp\left(-2\alpha_1 L_1\right), \tag{7}$$

where η_{12} – the power coupling efficiency from fiber 1 to fiber 2, η_{21} – the corresponding quantity in the reverse direction and $\eta_{12} = \eta_{21} = \eta$, S_2 – the backscatter coefficient of fiber behind the splice is given by:

$$S_2 = 0.038\,(\lambda/(n_2 W_2))^2\,. \tag{8}$$

With the assumption that the fundamental mode field distribution LP_{01} can be approximated by Gaussian distribution and connection of fibers whose axes are shifted by d quantity [2]:

$$\begin{aligned} \eta_{12} = \eta_{21} = &\left((2W_1W_2)/\left(W_1^2 + W_2^2\right)\right)^2 \cdot \\ &\cdot \exp\left(-2d^2/\left(W_1^2 + W_2^2\right)\right). \end{aligned} \tag{9}$$

One-way A_{12} splice loss from fiber 1 to 2 measured by a reflectometer is:

$$2A_{12} = -10\log\left(P_2/P_1\right) \tag{10}$$

Hence, using Eqs. (3), (6)–(9), one can receive:

$$P_2/P_1 = \left(n_1W_1/n_2W_2\right)^2 \eta_{12}\eta_{21}, \tag{11}$$

$$\begin{aligned} 2A_{12} &= -10\log\left(P_2/P_1\right) = \\ &= 20\log\left(n_2/n_1\right) + 20\log\left(W_2/W_1\right) + \\ &+ 40\log\left(0.5\left(W_1/W_2 + W_2/W_1\right)\right) + \\ &+ 20\log\left(\exp\left(2d^2/\left(W_1^2 + W_2^2\right)\right)\right). \end{aligned} \tag{12}$$

Eventually one-way splice loss from direction 1→2 measured by a reflectometer is:

$$\begin{aligned} A_{12} &= 10\log\left(n_2/n_1\right) + 10\log\left(W_2/W_1\right) + \\ &+ 20\log\left(0.5\left(W_1/W_2 + W_2/W_1\right)\right) + \\ &+ 4.34\left(2d^2/\left(W_1^2 + W_2^2\right)\right) \end{aligned} \tag{13}$$

and analogically one-way splice loss from direction 2→1 measured by a reflectometer is:

$$\begin{aligned} A_{21} &= 10\log\left(n_1/n_2\right) + 10\log\left(W_1/W_2\right) + \\ &+ 20\log\left(0.5\left(W_1/W_2 + W_2/W_1\right)\right) + \\ &+ 4.34\left(2d^2/\left(W_1^2 + W_2^2\right)\right). \end{aligned} \tag{14}$$

Splice loss is an arithmetical mean of (13) and (14) and is consistent with (1):

$$\begin{aligned} A_S &= 0.5 \cdot \left(A_{12} + A_{21}\right) + \\ &= 20\log\left(\left(W_1^2 + W_2^2\right)/2W_1W_2\right) + \\ &+ 4.34\left(2d^2/\left(W_1^2 + W_2^2\right)\right). \end{aligned} \tag{15}$$

3. Reflectometric measurement of splices with thermally expanded core area

Total losses of TEC area are a sum of losses resulting from the mismatch of mode field radii (after diffusion), axis shift and transmission losses T_f resulting from dimensions of TEC area [10]:

$$\begin{aligned} \Sigma = &-10\log\left[\left(2W_{diff1}W_{diff2}/\left(W_{diff1}^2 + W_{diff2}^2\right)\right)^2\right] + \\ &+ 4.34\left(2d^2/\left(W_{diff1}^2 + W_{diff2}^2\right)\right) - 10\log T_f, \end{aligned} \tag{16}$$

where W_{diff1}, W_{diff2} – mode field radii of connected fibers in the point of contact (after diffusion), in TEC.

For equalized, in the point of contact, mode field radii and their linear change in the transit area, the biggest splice loss of this area (the worst case) occurs for the minimal value of transmission coefficient T_f, described as [10, 11]:

$$T_f = T_A T_{B1} T_{B2} T_C, \tag{17}$$

where

$$T_A = \left[1 + \left\{0.5\left(\gamma_{\max 1} - 1\right)\left(\pi n_1 W_1^2/\lambda L\right)\right\}^2\right]^{-1}, \tag{18}$$

$$T_C = \left[1 + \left\{0.5\left(\gamma_{\max 2} - 1\right)\left(\pi n_2 W_2^2/\lambda L\right)\right\}^2\right]^{-1}, \tag{19}$$

$$T_{B1} = \left[1 + \left\{\gamma_{\max 1}\left(\gamma_{\max 1} - 1\right)\left(\pi n_1 W_1^2/\lambda L\right)\right\}^2\right]^{-1}, \tag{20}$$

$$T_{B2} = \left[1 + \left\{\gamma_{\max 2}\left(\gamma_{\max 2} - 1\right)\left(\pi n_2 W_2^2/\lambda L\right)\right\}^2\right]^{-1}, \tag{21}$$

where T_A, T_{B1}, T_{B2} and T_C – power transmission coefficient in points A, B_1, B_2 and C – Fig. 2, L – half of TEC area length – Fig. 2, $\gamma_{\max} = A_{diff}/a$ is a ratio of the core radius after diffusion to the core radius before diffusion, n – core refractive index, W – mode field radius, λ – wavelength.

In Eqs. (18)–(21) index 1 denotes parameters of the input fiber (e.g. G.655 [12] and index 1 denotes parameters of the output one, for example, G.652 [13]) – Fig. 2.

For calculations of the total splice loss (16) it is necessary to know diffusion coefficients of the core dopant of connected fibers, as well as, the length of TEC area – $2L$. Knowing diffusion coefficients, it is possible to calculate A_{diff} [4, 14]:

$$A_{diff} = \sqrt{a^2 + 4Dt}, \tag{22}$$

where D – diffusion coefficient, t – diffusion time.

Assuming Gaussian mode field distribution LP_{01}, we have [15]: $W = a\big/\sqrt{\ln V}$, where a and W are radii of the core and mode fields before diffusion. As the splice area (TEC) remains of single mode character after diffusion [4, 16] the normalized frequency $V = (2\pi/\lambda) \cdot aNA$ remains unchanged after diffusion, hence, $W_{diff}/A_{diff} = 1\big/\sqrt{\ln V}$.

For examinations of optimization of thermal connection and reflectometric measurements, the non zero dispersion shifted-single mode fibers (NZDS-SMF) of the type True-Wave – G.655 and the matched cladding single mode fiber (MC-SMF) of the type 1528 – G.652 with parameters given in Table 1, have been used. Furukawa S175 splicer has been applied.

Table 1
Parameters of connected fibers

Fiber type	$2W\|_{1310\text{ nm}}$ [μm]	$2W\|_{1550\text{ nm}}$ [μm]	Nominal core radius a [μm]
MC-SMF	9.2 ± 0.4*	10.5 ± 1*	4.0
NZDS-SMF	6.64**	8.4 ± 0.6*	3.0

* catalogue parameters, ** measurement

Without the optimization process aiming at formation of TEC area and matching mode fields, the splice loss of such fibers - without axis shift – is equal to (1): $A_\alpha|_{1310\text{ nm}} = 0.454$ dB and $A_\alpha|_{1550\text{ nm}} = 0.214$ dB, and one-way reflectometric losses (13) and (14): $A_{12}|_{1310\text{ nm}} = -0.962$ dB, $A_{21}|_{1310\text{ nm}} = 1.87$ dB, $A_{12}|_{1550\text{ nm}} = -0.755$ dB and $A_{21}|_{1550\text{ nm}} = 1.183$ dB.

Optimization of the fusion process of fibers with significantly different parameters involves increasing current (temperature) or fusion time or both parameters simultaneously [6, 17] – as compared to currents and fusion times of standard fibers SMF. The purpose of increasing time and fusion current is to diffuse the core dopant in the connected fibers so that mode field radii W_1 and W_2 would be equalized within the splice [6, 17]. Yet, it is safer to prolong only the fusion time as current increase causes temperature rise and may lead to melting rather than fusing the fibers.

In Fig. 3 and Fig. 4 measurements of one-way loss A_{12} and A_{21} of fiber splices of the type NZDS-SMF – MC-SMF are presented in the function of fusion time, and in Fig. 5 A_S loss is shown. Results for each splice are the average from 10 fusion tests. Measurements were performed with the use of reflectometer MW9076D/D1 of Anritsu company, for three measurement wavelengths: $\lambda = 1310$ nm, $\lambda = 1550$ nm and $\lambda = 1625$ nm.

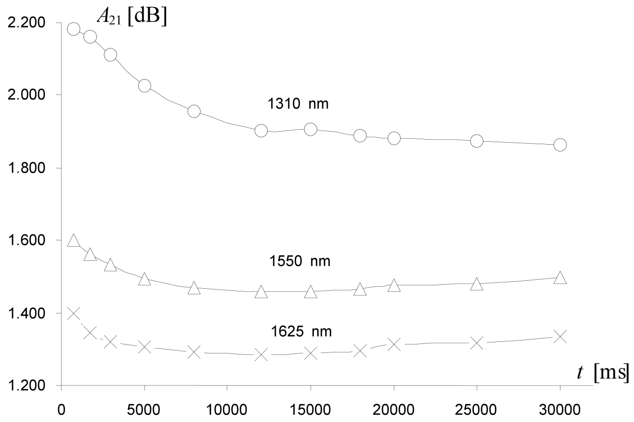

Fig. 3. Dependence of one-way splice loss A_{21} (for three measurement wavelengths) of fibers NZDS-SMF – MC-SMF on the fusion time – Furukawa S175 splicer, measurements were performed with the use of a reflectometer MW9076D/D1 of Anritsu company

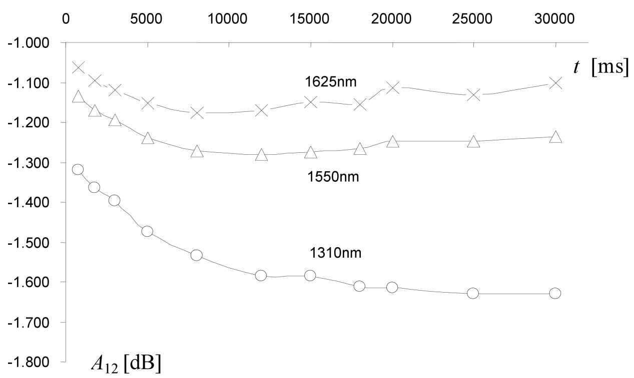

Fig. 4. Dependence of one-way splice loss A_{12} (for three measurement wavelengths) of fibers NZDS-SMF – MC-SMF on the fusion time – Furukawa S175 splicer, measurements were performed with the use of a reflectometer MW9076D/D1 of Anritsu company

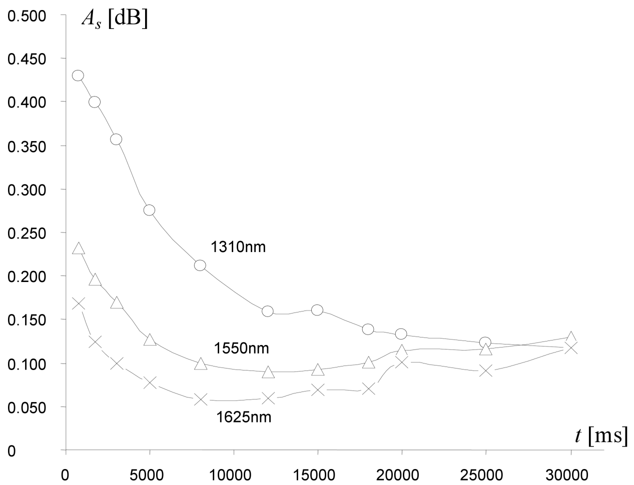

Fig. 5. Dependence of real splice loss A_S (for three measurement wavelengths) of fibers NZDS-SMF - MC-SMF on the fusion time - Furukawa S175 splicer

Real splice losses A_s, in a given time, decreases with the time increase – Fig. 5. Theoretically, it means a good match of mode fields of the connected fibers thanks to the dopant diffusion whereas, TEC area loss resulting from an increase of its crosswise dimensions rises [6].

Repeated results of one-way measurements of splice losses A_{12} and A_{21} courses in the function of fusion time – Fig. 3 and Fig. 4, prove that during the optimization process there takes place the match of mode field radii $W_1 \leftrightarrow W_2$. Thus, it can be noticed that $A_{21}^{(+)}$ (positive) decreases and $A_{12}^{(-)}$ (negative) increases with the fusion time increase – Fig. 3 and Fig. 4.

For a simple joint, without a transit area, A_{12} and A_{21} are described by expressions (13) and (14). In these expressions components: $10\log(n_2/n_1) + 10\log(W_2/W_1)$ for A_{12} and $10\log(n_1/n_2) + 10\log(W_1/W_2)$ for A_{21} result from the method of measurement and can not be subjected to optimization, as they depend on the backscatter of fibers used for fusion: expressions (6), (8) and (11). Only the components resulting from optical power coupling between spliced fibers, that is, $20\log(0.5\cdot(W_1/W_2 + W_2/W_1))$ or $20\log(0.5(W_1/W_2 + W_2/W_1)) + 4.34\left(2d^2/\left(W_1^2+W_2^2\right)\right)$ in the case of axes shift of connected fibers, undergo changes, both for A_{12} and A_{21}.

In case of reflectometric measurements analysis of TEC splice it is necessary to account additionally for transmission losses resulting from dimensions of the transit diffusion area:

$$\begin{aligned} A_{12} &= 10\log(n_2/n_1) + 10\log(W_2/W_1) + \\ &+ 20\log(0.5(W_1/W_2 + W_2/W_1)) + \\ &+ 4.34\left(2d^2/\left(W_1^2+W_2^2\right)\right) + C_{12}, \end{aligned} \tag{23}$$

$$\begin{aligned} A_{21} &= 10\log(n_1/n_2) + 10\log(W_1/W_2) + \\ &+ 20\log(0.5(W_1/W_2 + W_2/W_1)) + \\ &+ 4.34\left(2d^2/\left(W_1^2+W_2^2\right)\right) + C_{21}, \end{aligned} \tag{24}$$

$$\begin{aligned} A_S &= (A_{12} + A_{21})/2 + \\ &= 20\log(0.5(W_1/W_2 + W_2/W_1)) + \\ &+ 4.34\left(2d^2/\left(W_1^2+W_2^2\right)\right) + C, \end{aligned} \tag{25}$$

where C_{12} – always positive transmission loss for measurement from direction 1 to 2, C_{21} – always positive transmission loss for measurement from direction 2 to 1, $C = (C_{12} + C_{21})/2 = -10\log T_f$ (17) hence $A_S = A_\alpha - 10\log T_f$.

Thus, if (as in Fig. 4) $\left|A_{12}^{(-)}\right|$ grows (in Fig. 4, for $\lambda =$ 1310 nm; in the full scope of applied time ranges (periods), and for $\lambda = 1550$ nm and $\lambda = 1625$ nm from 750 to 15000 ms) it means that, because $10\log(n_2/n_1) + 10\log(W_2/W_1)$ remains negative, the always positive $20\log(0.5(W_1/W_2 + W_2/W_1)) + C_{12}$ or $20\log(0.5(W_1/W_2 + W_2/W_1)) + 4.34 \times \left(2d^2/\left(W_1^2+W_2^2\right)\right) + C_{12}$, in case of the axis shift, must decrease. This, in turn, means that W_1/W_2 approaches one – there follows a match of mode fields. Due to core dopant diffusion approaches W_2, but at the same time, mode field radii increase within the splice, which causes that $4.34\left(2d^2/\left(W_1^2+W_2^2\right)\right)$ (if there occurs axes shift of connected fibers) decreases, as well. The conclusion about the match of mode fields is confirmed by the fact that the positive C_{12} grows along with diffusion time as then, crosswise dimensions of TEC area increase.

Simultaneously, positive $A_{21}^{(+)}$ decreases (in Fig. 3, for $\lambda = 1310$ nm in the full range of applied times, for $\lambda = 1550$ nm and $\lambda = 1625$ nm from 750 to 15000 ms – Fig. 3.

Because $10\log(n_1/n_2)+10\log(W_1/W_2)$ remains permanently positive, thus permanently positive

$$20\log(0.5(W_1/W_2 + W_2/W_1)) + C_{21}$$

or

$$\begin{aligned} &20\log(0.5(W_1/W_2 + W_2/W_1)) + \\ &+ 4.34\left(2d^2/\left(W_1^2+W_2^2\right)\right) + C_{21}, \end{aligned}$$

in case of axes shift of connected fibers, must decrease. This is consistent with the fact that W_1/W_2 approaches one – there occurs a match of mode fields. Like before, the conclusion concerning about a match of mode field radii is confirmed by the fact that positive C_{12} grows along with the diffusion time, as then transverse dimensions of TEC area increase.

Increase in splice loss for exceeding the time of fusion by about 15000 milliseconds for $\lambda = 1550$ nm and $\lambda = 1625$ nm, with simultaneous entrance into loss saturation for $\lambda = 1310$ nm – Fig. 5, is caused, according to the authors, by the influence of occurring defects and the fiber structure faults which can be formed in the cladding due to a long fusion time. With the increase of λ the mode field increases and therefore, the disturbances in the cladding boost the splice loss, for bigger measurement wavelengths. It is also an indicator of the splice quality assessment and a signal for stopping increasing fusion time or current.

4. Comparison of reflectometric measurements and theoretical calculations of losses in thermally expanded core areas

Total optical power losses in TEC area are a sum of losses resulting from the mismatch of mode field radii and the transit area size, for example, first of all, from its length $2L$ and $\gamma_{\max}$. An analysis of the two variables allows for matching the thermal connection optimal time. For arc splicers the length of TEC area is approximately $2L = 700$ μm [6].

With the assumption of diffusion coefficients equality of the spliced fibers of different types, the minimum splice loss is not observed in dependence $A_\alpha(t)$ [18]. This splice loss decreases with longer diffusion time and with an increase of diffusion coefficient. This denies the results of experiments, for example [17, 19], thus, it is advisable to accept two different diffusion coefficients for different types of fibers, that is, for different concentration levels of the core dopant. Generally, with higher concentrations of dopants an increase of their diffusion coefficients can be observed [20]. The fusion temperature in Furukawa S175 splicer is 1900°C [18], this corresponds to diffusion coefficients of GeO_2 in SiO_2 in the range $D = 5 \times 10^{-14} \div 10^{-14}$ m^2/s [18, 21]. For NZDS-SMF fiber (higher concentration of core dopant) it was assumed $D = 5 \times 10^{-14}$ m^2/s [18], and for MC-SMF fiber (lower concentration of core dopant) it was assumed $D = 10^{-14}$ m^2/s. Calculation and experimental results, for $\lambda = 1310$ nm, are presented in Fig. 6.

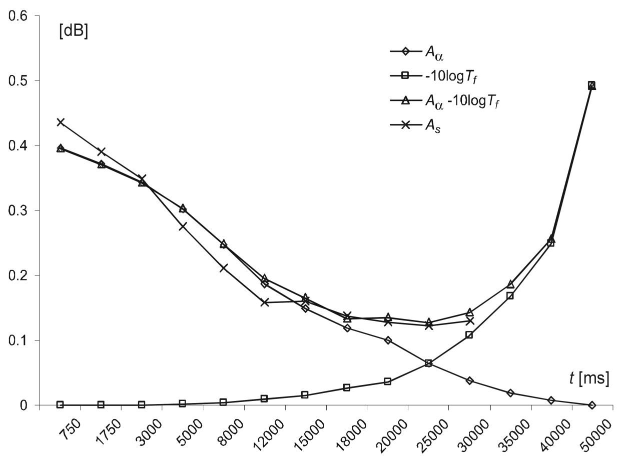

Fig. 6. Comparison of theoretical and experimental splice loss results

The experimental results of splice loss A_S – Fig. 5 reveal a good correlation with the simulation results for $\Sigma = A_\alpha - 10\log T_f$ – Fig. 6. Minimum of splice loss, for $\lambda = 1310$ nm, is obtained in the experiment and simulation for the same diffusion times, that is 25000 milliseconds and the difference of reached splice loss values in this point is 0.005 dB. Taking into consideration the fact that sensitivity of reflectometric measurements was 0.02 dB, the result for minimum loss can be considered as identical.

For the analyzed increases of connection times – Fig. 6 an increase in transmission loss: $-10\log T_f$ with simultaneous drop of loss: A_α connected with matching mode field radii, is characteristic [21].

5. Conclusions

The process of fusion optimization of fibers with significantly different parameters can be verified by one-way reflectometric measurements of the splice loss. The main advantage of one-way OTDR measurements is that they can be made from a remote location, far away from an actual fiber installation. Analysis of these measurements makes it possible to define explicitly whether there occurs matching mode fields of connected fibers, and when to finish the optimization process because of degradation of the splices.

Acknowledgements. This work was partly supported by the Polish Ministry of Science and Higher Education under the Grant NN517 397634.

REFERENCES

[1] A.W. Snyder and J.D. Love, *Optical Waveguide Theory*, Chapman and Hall, London, 1983.

[2] A. Majewski, *Theory and Design of Fibre Waveguides*, WNT, Warszawa, 1991, (in Polish).

[3] N. Tomoyuki, O.Taichi, K. Kengo, N. Masashi, and T. Kotaro, “Fiber for next-generation extra-large-capacity DWDM transmission”, *Hitachi Cable Rev.* 20, 3–6 (2001).

[4] K. Shiraishi, Y. Aizawa, and S. Kawakami, “Beam expanding fiber using thermal diffusion of the dopant”, *J. Lightwave Technol*. 8, 1151–1161 (1990).

[5] W. Zheng, O. Hulten, and R. Rylander, ”Erbium-doped fiber splicing and splice loss estimation”, *J. Lightwave Technol*. 12, 430–435 (1994).

[6] M. Ratuszek, J. Majewski, Z. Zakrzewski, and J. Zalewski, “Examination of spliced telecommunication fibers of the NZDS-SMF type adjusted for wavelength division multiplexing”, *Optica Applicata* 29 (1–2), 73–85 (1999).

[7] J.K. Barnovski and S.M. Jensen, ”Fiber waveguides: a novel technique for investigation attenuation characteristics”, *Appl. Opt*. 15, 2112–2115 (1976).

[8] M. Nakazawa, ”Rayleigh backscattering theory for single-mode optical fibers”, *J. Opt. Soc. Amer*. 73, 1175–1180 (1983).

[9] C.M. Miller, S.C. Metter, and I.A. White, *Optical Fiber Splices and Connectors*, Marcel Dekker Inc., New York, 1986.

[10] M. Ratuszek, “Analysis of loss of single mode telecommunication fiber thermally diffused core area”, *Optica Applicata* 37 (3), 279–294 (2007).

[11] M. Kihara, M. Matsumoto, T. Haibara, and S. Tomita, “Characteristics of thermally expanded core fiber”, *J. Lightwave Technol.* 14, 2209–2214 (1996).

[12] Recommendation ITU-T G.655, *Transmission Media Characteristics: Characteristics of a Non-Zero Dispersion Shifted Single Mode Optical Fibre Cable,* 2003.

[13] Recommendation ITU-T G.652, *Transmission Media Characteristics: Characteristics of a Single-Mode Optical Fibre Cable*, 2003.

[14] K. Shiraishi, T. Yanagi, and S. Kawakami, “Light-propagation characteristics in thermally diffused expanded core fibers”, *J. Lightwave Technol.* 11, 1584–1591 (1993).

[15] D. Marcuse, “Microdeformation losses of single mode fibers”, *Appl. Opt*. 23 (7), 1082 (1984).

[16] M. Ratuszek, J. Majewski, Z. Zakrzewski, and M.J. Ratuszek, “Analysis of loss of single mode telecommunication fiber thermally diffused core areas”, *Proc. SPIE* 6608, 1–5 (2007).

[17] W. Zheng, ”The real time control technique for erbium doped fiber splicing”, *Ericsson Rev*. 27, 1–24 (1993).

[18] M. Ratuszek, “Influence of temperature and length of splicing areas on the loss of joints of single mode telecommunication fibers”, *Proc. SPIE* 7120, 20–32 (2008).

[19] M. Ratuszek, J. Majewski, Z. Zakrzewski, and M.J. Ratuszek, “Process optimization of the arc fusion splicing different types of single mode telecommunication fibers”, *Opto-Electron. Rev.* 8 (2), 161–170 (2000).

[20] W. Jost, *Diffusion in Solids, Liquids, Gases*, Academic Press, New York, 1960.

[21] M. Ratuszek, Z. Zakrzewski, and J. Majewski, “Characteristics of thermally diffused transit areas of single-mode telecommunication fibers”, *J. Lightwave Technology* 27, 3050–3056 (2009).